Mapping prenoon auroral structures to the magnetosphere

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Abstract

All-sky auroral images acquired at Ny-Ålesund were used in conjunction with observations of a Polar overflight on November 30, 1997, to determine where prenoon, 0900-1000 magnetic local time (MLT) auroral structures map to the outer magnetosphere. Polar observations at midaltitudes are used to constrain the mapping between the aurora and the magnetosphere. The Tsyganenko 96 magnetic field model (T96), driven by interplanetary conditions and D_{ST}, is used for that mapping. When the T96 model is driven by conditions on this day, the open/closed field line boundary maps 2-3 degrees lower in latitude than observed for this day. By making an ad hoc adjustment to match the location of the model open/closed field line boundary to observations, we find that the agreement with other aspects of the observations is also improved. These include (1) Polar observations of the dayside extension of the boundary plasma sheet (BPS) (structured low-energy electrons, detected in a region of sunward convection and region 1 field-aligned currents) mapped to the ionosphere in a region of discrete aurora, (2) Polar observations of the central plasma sheet (high-energy electron precipitation) maps to diffuse green auroral emissions equatorward of the discrete aurora, and (3) Polar electric field observations are consistent with convective motions of the auroral forms and changing interplanetary magnetic field (IMF) conditions. When the all-sky images are mapped into the magnetosphere, we find that the discrete aurora identified with the BPS mapped to the outer dawnside edge of the magnetosphere. This mapping indicates that earlier Geotail reports of a sunward flowing mixing region in the equatorial magnetosphere [*Fujimoto et al.*, 1998] is really within the dayside extension of the BPS, compatible with both the low-altitude BPS observations of *Newell and Meng* [1992] and type 4 dayside aurora of *Sandholt et al.* [1998]. Since the Polar observations place the sunward flowing mixing region as a source of region 1 currents for this IMF B_Y positive case [*Farrugia et al.*, this issue], these results extend the source of the region 1 currents from the antisunward flowing low-latitude boundary layer into the sunward flowing BPS, commensurate with *Yamauchi et al.* [1998] and *Sonnerup* [1980].

1. Introduction

Knowledge of how processes in the magnetosphere affect the ionosphere has traditionally been obtained by field line mapping in increasingly more realistic geometries. This is an ongoing research program of great complexity. The field line mappings of *Tsyganenko and Stern* [1996] are extremely helpful in this respect and have allowed progress to be achieved in relating observations at different altitudes within the system. For example, *Maynard et al.* [1995] used T89 to map the *Heppner and Maynard* [1987] electric field patterns to the magnetosphere to show that significant fluxtube opening must occur away from the cusp in the flank. However, outstanding questions remain concerning the coupling between magnetospheric boundary layers and the ionosphere and their relationship to dayside auroral emissions. In view of this, and in view of how difficult it is to include all currents when mapping with the magnetospheric models, it is clearly helpful that they be checked against case studies. The present work and that of *Farrugia et al.* [this issue], is one such case study that brings to light aspects which call for further investigation.

One approach to studying magnetospheric ionospheric coupling is based upon inferring magnetospheric sources from the characteristics of precipitation in the ionosphere. *Newell and Meng* [1992] described dayside electron and ion precipitation as originating in five distinct source regions, the cusp proper, the mantle [*Newell et al.,* 1991a], the low-latitude boundary layer (LLBL), the boundary plasma sheet (BPS), and the central plasma sheet (CPS). LLBL precipitation contains a mixture of low-energy magnetosheath and higher energy magnetospheric plasmas and generally occurs in regions of antisunward plasma flow and region 1 field-aligned currents [*Newell et al.,* 1991b; *Bythrow et al.,* 1981]. The terms CPS and BPS are used here in the phenomenological sense of *Winningham et al.* [1975]. The BPS lies poleward of the CPS, has more spatially and spectrally structured electron precipitation than in the CPS, occurs in regions of sunward plasma flow, and either region 2 field-aligned currents [*Newell et al.,* 1991b] or region 1 field-aligned currents [*Yamauchi et al.,* 1998]. However, particle and current boundaries often do not coincide [*de la Beaujardiere et al.,* 1993]. Much progress has been attained by these investigations.

To some degree magnetospheric structures and electrodynamics image onto the ionosphere as auroral emissions. Much work has been done to identify the various plasma characteristics observed by low-altitude satellites, and their optical manifestations in the ionosphere. *Sandholt et al.* [1998] used meridian-scanning photometer measurements to characterize the dayside aurora into five types. Types 1 and 2 relate to the cusp for southward and northward directed interplanetary magnetic field (IMF), respectively. Red line (630.0 nm) type 1 auroral forms have sharp low-latitude borders with episodically occurring poleward moving auroral forms (PMAF). PMAF have velocity components in the eastward (westward) direction for positive (negative) IMF B_Y. Type 2 auroral forms are located further poleward, have a sharp poleward boundary and irregular borders on the equatorward side. The sharp poleward boundary results from merging on the poleward edge of the cusp during periods of northward IMF. Significant green line (557.7 nm) emissions often accompany the red line emissions at active merging sites. Type 3 aurora is a diffuse aurora that occurs extensively over all local times equatorward of the more discrete forms. Type 4 aurora occurs on the morningside of the cusp poleward of the diffuse type 3 aurora and are characterized by structured forms. Type 5 aurora are similar to those of type 4 but appear on the afternoon side of the cusp. Type 5 aurora often show stronger green line components than those of type 3. Auroral forms have also been categorized using Viking data [e.g., *Elphinstone et al.,* 1993].

Observations in the magnetosphere show the LLBL on the inner edge of the magnetopause at low latitudes to be a place where solar wind plasma, momentum, and energy, gain entry to the magnetosphere [*Eastman et al.,* 1976]. The *Eastman et al.* [1976] boundary layer was tailward flowing. The LLBL has also previously been described as having two layers [*Sckopke et al.,* 1981]. The outer LLBL contains magnetosheath plasma on open field lines that convect tailward. The inner LLBL holds both magnetosheath and magnetospheric plasma on closed magnetic field lines that convect sunward [*Fujimoto et al.,* 1997, 1998; *Ogilvie et al.,* 1984]. This inner portion of the magnetospheric LLBL has been referred to as the mixing region.

The aim of this paper is to identify the magnetospheric source regions of the particle precipitation producing the types 3 and 4 aurora observed over Ny-Ålesund on November 30, 1997, near 0900 magnetic local time (MLT). To do this we use the Tsyganenko 96 magnetic field model (T96) to map the all-sky im-

ages of the aurora out to the magnetosphere. A strong constraint on this mapping is provided by Polar observations at midaltitudes near 6 R_E. In a companion paper, *Farrugia et al.* [this issue] concentrate on the temporal evolution of this mapping and its relationship to the interplanetary parameters.

2. Instrumentation

Polar was launched into a 90-degree inclination orbit with an apogee of 9 R_E over the northern polar cap, a perigee of 1.8 R_E, and an orbital period of 17.5 hours. Measurements from the instruments used in this study include the Hydra electron/ion spectrometer [*Scudder et al.*, 1995], the electric field instrument (EFI) [*Harvey et al.*, 1995], and the magnetic field experiment (MFE) [*Russell et al.*, 1995]. Observations from IMP 8 [*Scearce et al.*, 1976] and Wind [*Ogilvie et al.*, 1995; *Lepping et al.*, 1995] are used to characterize the IMF and solar wind velocity conditions. The ground aurora sensor is an all-sky camera (ASC) located in Ny-Ålesund, Svalbard. In this study we make use of ASC images at the red 630.0-nm and green 557.7-nm emission lines, collected at approximately 30-s intervals.

3. Observations

On November 30, 1997, the footprint of Polar crossed the ASC's field of view between about 0540 and 0715 UT; however, ASC imaging did not begin until 0600 UT. During this time the Wind and IMP 8 satellites were located near GSM coordinates of (195, 2, 28) R_E and (31, -1, -1) R_E, respectively. Figure 1 shows measurements from both spacecraft versus the time of IMP 8 observations with the Wind data lagged. Plotted from top to bottom are IMF B_X, B_Y, and B_Z. Since the average solar wind velocity was 310 km/s, the estimated lag time delay between Wind and IMP 8 is ~56 min. The agreement between the Wind and IMP 8 observations using the 56-min delay is good. *Farrugia et al.* [this issue] considers the further propagation from IMP 8 to the shock, propagation in the magnetosheath, and Alfvén transit times in the magnetosphere in order to set the applicable lag between Wind and Polar at 78 min. During the time of the Polar overflight (0600 to 0715 UT), the appropriately lagged (0538 to 0653 UT) IMF B_X was positive and B_Y was mostly negative. IMF B_Z was near zero from 0600 to 0624 UT and from 0645 to 0730 UT. Between 0624 and 0645 UT the IMF turned strongly northward. Thus, with the exception of a short inter-

val of B_Z domination, the prevailing IMF direction after 0538 UT is in the XY plane with nearly equal negative B_Y and positive B_X.

Plate 1 shows the Polar Hydra, MFE, and EFI observations for November 30, 1997. Plates 1g and 1h show electric field measurements presented in an inertial frame of reference. Plate 1h shows the electric field component along the spacecraft velocity vector. Plate 1g integrates that electric field to obtain the potential distribution along the orbit track. The Polar spacecraft was descending from apogee, moving almost southward, so a positive (negative) polarity of electric field can be viewed as driving eastward (westward) or sunward (antisunward) plasma flow. At 0512 UT the electric field reversed and the integrated potential had a maximum (morningside convection reversal) coincident with the first observations of the kilovolt ions and low-energy electrons (Plates 1a and 1e). However, the potential decreases slowly until 0600, when IMF B_Z began to decrease toward zero at 0538 UT (22 min earlier), and then the potential decreased at a slightly faster rate. The interval in Plate 1 from 0644 to 0700 UT, when the IMF was positive B_Z (about 0622 to 0645 UT in Figure 1), was characterized by long-period oscillations in the plasma drifts. Following 0700 UT much smaller and more rapid variations in the drift velocity occurred. Since the high-altitude satellite was moving slowly, temporal and spatial variations are mixed together. The temporal variation aspects of these measurements are discussed by *Farrugia et al.* [this issue]. Note that the interval after 0515 UT is dominated by sunward flowing plasma (Plate 1h).

Plates 1a-1e show Polar/Hydra measurements from 0500 to 0730 UT in the form of energy versus time spectrograms. Plotted from top to bottom are the omnidirectional fluxes of energetic ions, the ion anisotropies, ion skews, electron anisotropies, and omnidirectional fluxes of energetic electrons. The measured energies of the ions and electrons has been shifted to E_{debye} by the spacecraft potential (Φ) where $E_{debye} = E_{measured} + q\Phi$. The spectra are also corrected according to the Liouville theorem so that the counts and flux presented are those that a hypothetically uncharged spacecraft would see. The ion skew shows the ratio of field-aligned ($0° - 30°$) and field-apposed ($105° - 180°$) ion fluxes along a magnetic field line. For example, an ion skew of 10 in the field-aligned direction (red) means that the ion flux up the field line is 10 times larger than the ion flux down the field line. The ion and electron anisotropy show

the ratio of field-aligned (average of the aligned and apposed) and trapped ($75° - 105°$) fluxes. A trapped (field-aligned) distribution would appear as blue or purple (yellow or red) in the anisotropy spectrograms.

From 0500 to 0515 UT, Polar detected no significant ion or electron fluxes, characteristic of the polar cap. The interval 0515 to 0600 UT is characterized by variable low-level ion and electron fluxes similar in energy to those commonly detected in the magnetosheath. It began with three bursts of low-energy electrons and kilovolt ions followed by very low flux levels. Higher energy electrons appeared after 0600 UT, which tended to have greater perpendicular than parallel fluxes. Higher energy ions also began to appear around 0600 UT with generally larger perpendicular than parallel fluxes, particularly after 0630 UT. Fluxes of low-energy electrons and sporadic kilovolt ions persisted until 0642 UT. Intensifications in the fluxes of low-energy electrons are anticoincident with those at high energies. The electron anisotropy (Plate 1d) shows that the fluxes of low-energy electrons are field-aligned. *Farrugia et al.* [this issue] argue from the electron bidirectional field-aligned distributions that this is a closed field line region. Two downward bursts of field-aligned keV ions occurred at 0611 and 0628 UT (red areas in Plate 1c). The lowest energy electrons and keV ions disappear at 0642 UT. The electric field data show that convection is in the sunward direction. Thus the region between 0600 and 0642 would be identified by *Newell et al.* [1991b] as BPS. After 0642 UT, trapped high-energy ion and electron fluxes are observed which are characteristic of the CPS.

Plate 1f shows the B56 component of the magnetic field (perpendicular to the spin plane), which is approximately in the east-west direction (positive westward). The International Geomagnetic Reference Field (IGRF) has been subtracted to remove the background. Variations in this component can be used to identify field-aligned currents. The generally negative slope from about 0555 to 0642 UT (or $78.7°$ to $75.4°$ ILAT corresponding to 26 to 15.7 L in Plate 1f) followed by the generally positive slope from 0642 to 0700 UT (or $75.4°$ to $73.8°$ ILAT corresponding to 15.7 to 12.8 L in Plate 1f) indicate that Polar first crossed the downward region 1 current sheet and then the upward region 2 current sheet [*Farrugia et al.*, this issue]. Superposed on these large-scale current systems are modulations in the magnetic field that are also apparent in the electric field observations. In so far as can be determined, the region 1/region 2 transi-

tion boundary coincides with the BPS/CPS particle boundary. Note that this places the sunward flowing BPS in the region 1 current region. This agrees with the observations of *Yamauchi et al.* [1998] and the theoretical picture of the boundary layer of *Sonnerup* [1980] (see his Figure 1). It also places region 2 currents in the region where the strong coherent oscillations are observed in the electric field. These are discussed by *Farrugia et al.* [this issue] (Note that the B_{56} direction is opposite to that of the similar Z component of *Farrugia et al.* [this issue]).

Plate 2 shows a time series of 630.0-nm and 557.7-nm ASC images acquired during the Polar overflight. Geographic north, south, east, and west are toward the top, bottom, right, and left sides of the figures, respectively. The universal time of the images are displayed in the top, left corners of the panels. The MLT of Ny-Ålesund is $MLT = UT + 3$ hours. A grid of geomagnetic longitude and latitude has been overlaid on the projections. The geomagnetic coordinate system is defined so that the Z axis is parallel to the magnetic dipole axis. The geographic coordinates of the dipole axis were located using the IGRF model. The black dot to the left of the N is the location of Ny-Ålesund. The white spot in the upper right corner of the images is caused by the instrument. The red (green) ASC images were projected to 200 (120) km. These altitudes were found to produce the best agreement between the intensity of electron fluxes observed by Polar and structures in the ASC images.

Plates 2a-2d show a time series of 630.0-nm ASC images; Plates 2e-2h show the 557.7-nm sequence of images. Apparent are discrete auroral forms and fainter diffuse auroral emissions. Discrete auroral forms are observed in the series of red images between about $74°$ and $77°$ magnetic latitudes. These auroral forms are typical of the type 4 aurora. *Sandholt et al.* [1998] suggested that they are caused by precipitation from the outer plasma sheet (BPS). Near the northern border of the type 4 aurora is a stable arc that appears in all the red images located between $76°$ and $77°$ magnetic latitude in the series but is not prominent in the green images. The discrete aurora south of the stable arc are more transient, and there are also multiple green forms. Just to the south of the discrete type 4 auroral forms are the diffuse emissions. The diffuse aurorae have stronger green than the red line emissions and are typical of type 3 aurorae. *Sandholt et al.* [1998] suggest that they are caused by electron precipitation from the plasma sheet (CPS). The diffuse type 3 aurora is the most intense in image Plate

2g.

The series of ASC images from which these samples have been extracted have been combined to create a movie to examine the temporal variations in the images. As may be inferred from Plate 2, the movie shows that the polewardmost form was stable. It also shows that discrete type 4 auroral forms south of the stable arc generally moved in the sunward or eastward direction. The rayed structures on the northern edge of the images poleward of the stable arc generally moved in the antisunward or poleward direction. However, the individual arcs do not move very far during there existence. Different arcs appear and disappear due to temporal variations superposed on the convective flow. It is the combined motion of a series of optical forms taken together in the movie that has allowed us to see the convective pattern at this time. Figure 2 illustrates the motion of the aurorae observed in the ASC images. The aurora sketched in Figure 2 has been drawn to match the aurora in Plate 2a but is meant to be representative of all of the images in the series. Represented in the drawing of Figure 2 are the regions where the discrete type 4 aurora and the diffuse type 3 aurora are observed. The region of type 3 aurorae is shaded and is at the bottom right side of the drawing. The discrete type 4 auroral forms are represented schematically by the elongated ovals, with the stable form to the north being cross-hatched. The observed motion of the aurora over the entire time interval, sunward (eastward) at lower latitudes with antisunward (poleward) motion at higher latitudes north of the stable arc, is indicated with arrows.

This flow pattern is consistent with expectations for a morning convection cell. Thus the background flow pattern derived from the movie restricts the convection reversal between sunward and antisunward flow to be at the stable arc.

To relate the aurora to the Polar measurements, each image in Plate 2 is overlaid with two representations of mapped Polar trajectories. Circles indicate the mapped positions of Polar at the time which that image was accumulated. The right one is determined from the T96 magnetic field model, mapping the Polar trajectory to the projected height of the auroral image. T96 uses as inputs the IMF, solar wind velocity, and density as measured by the Wind spacecraft and also the measured D_{ST} index. Clearly, this mapping gives good qualitative agreement between the Polar and optical observations, but in this case detailed quantitative agreement is not attained.

To further test the mapping, we used T96 to map the location of the aurorae seen in the ASC images out into the magnetosphere. From this mapping we have determined the location in the ASC image of the open/closed magnetic field line boundary in the model. The ionospheric projection of this boundary maps to latitudes of about 74°-75° latitude for this time and location. This means that Polar would have crossed the model open/closed field line boundary at ~ 0630 UT. However, from the particle observations we know that Polar detected significant plasma sheet electrons already at 0600 UT. The electric fields also indicate that it is sunward flowing in the whole intervening region. We know from observations that the open/closed boundary is at or poleward of the flow reversal boundary [e.g., *Heelis et al.*, 1980; *Lyons et al.*, 1996]. Therefore the model location of the open/closed field line boundary for this time period and location is at too low a latitude compared to the convection reversal boundary determined from the optics of between 76° and 77°.

Since the open/closed field line boundary in the model must be located at the same latitudes or higher latitudes than the observed convection reversal boundary, we have made an ad hoc adjustment to the model to move the open/closed field line boundary further northward. To minimize the adjustments to the model, we have moved the projection of the open/closed field line boundary up to near 76° latitude, commensurate with the location of the stable-arc convection-reversal boundary in the images. This adjustment was achieved by reducing the dynamic pressure input to the model from 4.8 to 0.8 nPa. This caused the model magnetopause to expand and the ionospheric projection of the open/closed field line boundary moved to higher latitudes. This was the only input parameter that could produce a significant change in the boundary location. The results of using the adjusted model to map Polar down to the ionosphere are also shown in Plate 2 as the westwardmost projection of the Polar trajectory on the images. Implications of this adjustment are addressed in the Discussion section.

We now investigate the reasonableness of this adjustment by looking at other features in the resulting mapping. When we compare the Hydra observations with the aurora emissions at the foot point of Polar using the adjusted model, we find that there are several points of favorable comparison. For example, at 0600 UT, when Polar is near the edge of the BPS precipitation, the foot point of Polar is near

the eastern end of the stable arc (Plate 2a). While Polar is in the BPS, several enhancements of low- and high-energy electron fluxes are observed. The enhancements in the high-energy electron fluxes correspond directly with the discrete auroral arcs seen in the ASC images. The discrete auroral arcs are a persistent feature of the aurora during this interval suggesting that the variations in the electron fluxes observed at Polar are spatial structures rather than temporal. Two examples of this correspondence are at 0622 and 0634 UT. At 0622 UT, Polar observes an enhancement of high-energy electrons accompanied with reduced fluxes of lower energy electrons. At the same time the foot point of Polar crossed over a discrete red auroral form (Plate 2b) and a discrete green auroral form (Plate 2f). Again at 0634 UT Polar observed an enhancement in the high-energy electrons with a reduction in the lower energy electrons. At this time Polar crosses over a green auroral form (Plate 2g). At 0642 UT, Polar began to observe the CPS. The images at 0640 show the foot point of Polar crossing out of the type 4 aurora and approaching the region where type 3 diffuse auroral emissions intensify. The relationship between the enhancements in the electron fluxes observed at Polar and the discrete aurora observed below Polar are also discussed in a companion paper by *Farrugia et al.* [this issue].

The agreement of the particle measurements with the auroral emissions allows us to consider qualitatively to where the auroral forms in the closed field line part of the ASC image map in the magnetosphere. Figure 3 summarizes the results of using the adjusted T96 model. The top illustration in Figure 3 is to be compared with Figure 2 and the ASC images. Geographic north, south, east, and west, and magnetic north look directions are labeled around the edge of the illustration. The location of the type 4 aurora, BPS precipitation, is marked by the horizontal lines. The stable arc is shown at the poleward edge of this region. The location of the type 3 aurorae, CPS precipitation, is shown with a shaded region. The bottom illustration of Figure 3 schematically summarizes the results of mapping the locations of the aurora out into the magnetosphere. The projection is shown in the equatorial plane of the magnetosphere. The Earth is shown in the center of the picture with the sunward direction downward, marked by an arrow. A bolder line approximates the magnetopause by marking the location of the open/closed field line boundary in the adjusted model. The morning side of that line maps to the hook shown in the upper right of the top illus-

tration. The locations where the type 3 and type 4 aurora map to are shown by the shaded region and the vertical lines, respectively. Comparing the two illustrations, we see that the type 4 aurorae and dayside BPS precipitation map to a narrow region along the flank of the magnetosphere. The type 3 aurorae and CPS precipitation map to the dayside inner magnetosphere adjacent to and Earthward of the BPS. The region inside of the hook in the ionospheric sketch contains open field lines. These open field lines would either map to the open LLBL or to the mantle and lobe. Field lines poleward of the discrete type 4 aurora, which the optics indicate are antisunward flowing, may either be open field lines or closed field lines that map back into the distant magnetotail.

4. Discussion

We have presented a case study where we tried to map auroral features to the magnetosphere. For this we used the T96 model. The model gave good qualitative agreement, but to enforce further agreement, particularly on the location of the open/closed field line boundary (well determined by the observations) we adjusted the dynamic pressure. In this way a good overall qualitative agreement with various features of the observations was achieved. While this does not provide an unique mapping, it does improve the agreement between the energetic particle and auroral emission observations. With this caution in mind, we used the adjusted T96 model to map entire ASC images to the magnetosphere. We caution that this is at best a qualitative mapping; however, the general regions that we map to in the magnetosphere provide us insight, even if the exact details of the mapping are model dependent. After a brief discussion of mapping issues, we then consider some implications for understanding magnetospheric sources of dayside auroral structures.

Maynard et al. [1995] mapped the *Heppner and Maynard* [1987] potential patterns to the equatorial plane using the T89 magnetic field model [*Tsyganenko*, 1989]. The mapped convection of the large dawnside cell for negative B_Y spreads out, turns toward, and reverses in the boundary layer. This is consistent with the implied patterns of Figures 2 and 3 using the adjusted T96 model. However, it is necessary to understand the implications of the adjustment. For this purpose we mapped magnetic field lines using the T89 model for $K_P = 2$, the T96 model with actual solar wind conditions, and the T96 model

with conditions modified as discussed earlier. Note that this is a case with low magnetic activity (hence $K_P = 2$) but higher than average dynamic pressure (4.5 nPa). In both the T89 model with $K_P = 2$ and the T96 model using actual solar wind condition the open/closed boundary is placed at a lower latitude than it was observed on this day. Our ad hoc adjustment flares the boundary nearer to that of T89 as well as expanding the dayside magnetosphere to move the cusp poleward, nearer to where it is observed as Ny-Ålesund rotates under it a half hour later. The net result is that the cusp is positioned further to the north for this high-dynamic-pressure, low-activity, solstice condition than the T96 magnetic field model predicts. This suggests that a change is needed in the dayside configuration in the cusp region in order to allow the subsolar magnetopause to conform to statistical and actual positions determined from observations.

We note that, in addition to the high dynamic pressure coupled with low activity and solstice, IMF B_X may also play a role in the dayside configuration. *Maynard et al.* [2000] have shown that B_X is important in the timing of the interaction with the solar wind, and *Crooker* [1992] noted that B_X serves to add (or subtract) equivalent dipole tilt in the interaction process driven by antiparallel merging. The positive B_X in this case could be expected to increase the effective dipole tilt. Closed field lines, as defined by T96, which map from the ionosphere poleward of the stable arc in Figure 3, extend back along the flank of the magnetotail beyond X = -10 R_E. At some point this region in reality transitions to lobe field lines and probably a small central lobe cell in the center of the large cell of the Heppner-Maynard DE pattern (analogous to *Crooker et al.* [1998] and *Burke et al.* [1994] results for positive B_Y). The remaining discussion comments on the implications of the data when we accept the mapping of the adjusted model, which we believe is a better representation of the indicated high-latitude mapping.

The movie of the ASC auroral images allowed us to examine the dynamic variations that occurred in the aurora during the Polar overflight. From the movies we identified a stable auroral form at the poleward boundary of the BPS precipitation. Previous observers have also found that the most prominent arcs observed at this MLT were along the boundaries of the boundary regions [*Newell et al.*, 1992]. The movie also showed that discrete auroral forms south of the stable arc generally moved sunward while rayed structures north of the stable arc moved antisunward. This

motion established the applicable morningside convection pattern with its reversal located on the stable arc on the northern edge of the region identified as BPS. This auroral motion observed in the movies is consistent with the electric field drifts derived from the Polar/EFI observations; however, it does pose one problem. The convection reversal boundary was observed by Polar at 0512 UT, well before Polar mapped to the edge of the stable arc just prior to 0600 UT. We note from Figure 1 that the interval from near 0515 to 0550 is a region of positive B_Z with negative B_Y. With these smaller clock angles we would expect an enlarged lobe cell driven by the positive B_Z, a region of sunward convection extending farther toward the pole [*Burke et al.*, 1994]. As B_Z returns to near zero and the auroral imaging begins, Polar maps to the end of the stable arc where sunward convection may be expected. Thus the extended period of sunward convection before 0600 UT is expected from the time-varying IMF, and the lobe cell interpretation is consistent with the low-level particle fluxes seen over the interval from 0530 to 0550 UT. The flow poleward at the eastern end of the stable arc is either into the merging line region or to field lines that map back along the flank magnetopause. Some of the motion poleward of the arc is most likely lobe related also.

Just equatorward of the convection reversal Polar encountered structured fluxes of electrons and ions. Each species showed two distinct energy populations that shared the same physical space. In both instances the fluxes of the low-energy populations were field-aligned and the high-energy population trapped (pitch angle distributions peaked near 90 degrees) at the altitudes of Polar. Near the ionospheric footprints of the particle structures crossed by Polar the ASC detected stable and ephemeral auroral forms. These auroral structures have been identified as type 4 auroral emissions in the nomenclature of *Sandholt et al.* [1998].

The observed distribution of structured low-energy electrons, detected in a region of sunward convection suggests that they are of BPS origin [*Newell et al.*, 1991b]. However, the total high- and low-energy populations detected at middle altitudes by Polar also show strong spectral similarities with particles detected by Geotail in the magnetospheric mixing region [*Fujimoto et al.*, 1997]. *Fujimoto et al.* [1997] identified the mixing region as low-density (0.5 cm^{-3}) hot plasma sheet ions (2.5 keV) mixed with low-energy magnetosheath-like ions (< 1 keV). This suggests that the dayside extension of the BPS and the magne-

tospheric mixing region represent the same location. The fact that both appear in regions of sunward convection just equatorward/earthward of the convection reversal is consistent with this hypothesis. The outward mapping of the aurora into the magnetosphere show that the region of type 4 aurora and BPS precipitation map to a narrow region along the flank of the magnetosphere. This is also consistent with our identification of this region as the same region as the mixing region observed by Geotail [*Fujimoto et al.,* 1997]. The Polar measurements for this event show that the BPS is associated with region 1 currents [see also *Farrugia et al.,* this issue]. This indicates that in the hemispheric location where high-latitude merging is expected (dawnside for negative B_Y), the sunward flowing BPS may be an additional source of Region 1 currents. Region 2 in this case was found associated with the CPS fluxes.

Equatorward of the mixing region, particle fluxes hardened so that Polar observed only the high-energy components. This corresponds to the satellite entering the region of dayside CPS precipitation [*Newell and Meng,* 1992]. The mapping to the magnetosphere is consistent with our interpretation of the source for intense green line emissions being in the central plasma sheet. While the discrete arcs mapped near the dawnside boundary, the region of the ASC image filled with diffuse green auroral emission mapped to the prenoon dayside magnetosphere adjacent to the boundary layer. The observed motion of the auroral forms in the magnetosphere was generally sunward into the boundary layer. We would expect that the CPS region in the magnetosphere would extend back in local time and map to auroral latitudes equatorward of the discrete aurora at earlier magnetic local times in the ionosphere.

In the adjusted mapping we have identified a mixing region on sunward flowing field lines with BPS precipitation that extends into the dayside at dawn. The *Fujimoto et al.* [1998] sunward flowing mixing region was also found near the magnetopause, sunward of the terminator at positive X_{GSM} values, between 0600 and 0900 MLT, consistent with the cartoon in Figure 3. Using Polar, we have regionally tied together, along magnetic field lines, the *Fujimoto et al.* [1997] mixing region observations with the *Newell et al.* [1991b] BPS precipitation and the *Sandholt et al.* [1998] type 4 aurora. Had we overadjusted the magnetic field model, the net result would be to move the mixing region down the flank. However the consistency of the data sets argues for the mapping presented.

Farrugia et al. [this issue] have shown that the IMF electric field variations may be a detailed time-varying driving source for variations within this region. The time lag to the satellite data established in that study was somewhat longer than the best calculated time, which they attributed to the possible need to propagate the IMF further back in the magnetosheath before the interaction takes place. The mapping to the dawnside flank that we have done here provides further reason to place coupling to this region away from the cusp. The exact mechanism is not revealed by these studies.

5. Summary

We have presented the results of mapping the ASC image to the magnetosphere to determine the source regions of the particle precipitation producing dayside auroral emissions. Particle flux observations from Polar at midaltitudes were used to test magnetic field model mapping between the Polar spacecraft and the ionosphere. We also checked the mapped magnetopause location in the ionosphere with the locations of the aurora. While in qualitative agreement with the observation for this time, the T96 model placed the open/closed field line boundary at too low a latitude. By making an ad hoc adjustment to T96, we have brought the model and observations from both Polar and the ground ASC into better agreement.

Using the adjusted model we have mapped whole ASC auroral images to the magnetosphere. Discrete type 4 aurora is found to map to BPS precipitation observed at Polar and the BPS previously seen westward of the cusp by *Newell et al.* [1991b]. The time interval during which Polar-observed BPS precipitation bracketed the region where the foot point of Polar was on field lines containing type 4 aurorae. Structure observed in the BPS contained spatial layers evidenced by the multiple discrete auroral forms observed in the ASC images. The diffuse green aurorae mapped to the plasma sheet precipitation observed at Polar. A smooth transition from red-dominated to green-dominated diffuse auroral emissions was observed at the foot points of Polar where Hydra observed an increase in the average energy of precipitating plasma sheet electrons.

From a movie of auroral images we identified a stable arc located near the northern boarder of discrete auroral emissions. This stable arc marked the northern edge of the BPS or mixing region precipitation.

Also from the movie an apparent motion of the auroral forms was observed. This motion was generally sunward south of the stable arc and antisunward or poleward north of the stable arc. This auroral motion observed in the ASC images is consistent with the electric field observations from Polar and with the expected convection pattern when IMF variations are considered. It is the existence of this stable arc and the configuration of motion around it that strongly argues that the T96 cusp must be moved poleward under these conditions; hence the adjustment to the model was done.

When the whole ASC images were mapped to the magnetosphere, the discrete type 4 aurora projected near the dawnside boundary where Geotail has previously observed a mixing region. The diffuse green auroral emissions mapped to the prenoon dayside magnetosphere adjacent to the mixing region. Auroral motion in the magnetosphere was generally sunward into the mixing region. These results identify the sunward flowing mixing region observations by Geotail on the dawn flank of the magnetosphere with the dayside extension of the BPS as identified by *Newell et al.* [1991b]. As such this region is the source of the type 4 aurora [*Sandholt et al.*, 1998].

References

Burke, W. J., E. M. Basinska, N. C. Maynard, W. B. Hanson, J. A. Slavin, and J. D. Winningham, Polar cap potentials during periods of positive B_Y and northward IMF, *J. Atmos. Terr. Phys., 56,* 209, 1994.

Bythrow, P. F., R. A. Heelis, W. B. Hanson, and R. A. Power, Observational evidence for a boundary layer source of dayside region 1 filed-aligned currents, *J. Geophys. Res., 86,* 5577, 1981.

Crooker, N. U., Reverse convection, *J. Geophys. Res., 97,* 19363, 1992.

Crooker, N. U., J. G. Lyon, and J. A. Fedder, MHD model merging with IMF B_Y: Lobe cells, sunward polar cap convection, and overdraped lobes, *J. Geophys. Res., 103,* 9143, 1998.

de la Beaujardiere, O., J. Watermann, P. Newell, and F. Rich, Relationship between birkeland current regions, particle precipitation, and electric fields, *J. Geophys. Res., 98,* 7711, 1993.

Eastman, T. E., E. W. Hones Jr., S. J. Bame, and J. R. Asbridge, The magnetopause boundary layer: Site of plasma, momentum and energy transfer from the magnetosheath into the magnetosphere, *Geophys. Res. Lett., 3,* 685, 1976.

Elphinstone, R. D., D. J. Hearn, J. S. Murphree, L. L. Cogger, M. L. Johnson, and H. B. Vo, Some UV dayside auroral morphologies, in *Auroral Plasma Dynamics, Geophys. Monogr. Ser.,* Vol. 80, edited by R. L. Lysak, p. 31, AGU, Washington, D. C., 1993.

Farrugia, C. J., P. E. Sandholt, N. C. Maynard, W. J. Burke, J. D. Scudder, D. M. Ober, J. Moen, and C. T. Russell, Pulsating midmorning auroral arcs, filamentation of a mixing region in a flank boundary layer, and ULF waves observed during a Polar-Svalbard conjunction, *J. Geophys. Res.,* this issue.

Fujimoto, M., T. Mukai, H. Kawano, M. Nakamura, A. Nishida, Y. Saito, T. Yamamoto, and S. Kokubun, Geotail observations of the low-latitude boundary layer, *Adv. Space Res., 20,* 813, 1997.

Fujimoto, M., T. Mukai, H. Kawano, M. Nakamura, A. Nishida, Y. Saito, T. Yamamoto, and S. Kokubun, Structure of the low-latitude boundary layer: A case study with Geotail data, *J. Geophys. Res., 103,* 2297, 1998.

Harvey, P., et al., The Electric Field Instrument on the Polar Satellite, *Space Sci. Rev., 71,* 583, 1995.

Heelis, R. A., J. D. Winningham, W. B. Hanson, and J. L. Burch, The relationship between high-latitude convection reversal and the energetic particle morphology observed by atmosphere explorer, *J. Geophys. Res., 85* 3315, 1980.

Heppner, J. P., and N. C. Maynard, Empirical high-latitude electric field models, *J. Geophys. Res., 92,* 4467, 1987.

Lepping, R. P., et al., The WIND magnetic field investigation, *Space Sci. Rev., 71,* 207, 1995.

Lyons, L. R., G. Lu, O. de la Beaujardiere, and F. J. Rich, Synoptic maps of polar caps for stable interplanetary magnetic field intervals during January 1992 geospace enviroment modeling campaign, *J. Geophys. Res., 101* 27,283, 1996.

Maynard, N. C., W. F. Denig, and W. J. Burke, Mapping ionospheric convection patterns to the magnetosphere, *J. Geophys. Res., 100,* 1713, 1995.

Maynard, N. C., et al., Dayside convection with northward IMF: Observations of a sounding rocket launched from Svalbarb, *J. Geophys. Res., , 105,* 5245, 2000.

Newell, P. T., and C.-I. Meng, Mapping the dayside ionosphere to the magnetosphere according to particle precipitation characteristics, *Geophys. Res. Lett., 19,* 609, 1992.

Newell, P. T., W. J. Burke, C.-I. Meng, E. R. Sanchez, and M. E. Greenspan, Identification of the plasma mantle at low altitudes, *J. Geophys. Res., 96,* 35, 1991a.

Newell, P. T., W. J. Burke, E. R. Sanchez, C.-I. Meng, M. E. Greenspan, and C. R. Clauer, The low latitude boundary layer and the boundary plasma sheet at low altitude: prenoon precipitation regions and convection reversal boundaries, *J. Geophys. Res., 96,* 21,013, 1991b.

Newell, P. T., C.-I. Meng, and R. E. Huffman, Determining the source region of auroral emissions in the prenoon oval using coordinated Polar BEAR UV-imaging and DMSP particle measurements, *J. Geophys. Res., 97,* 12245, 1992.

Ogilvie, K. W., R. J. Fitzenreiter, and J. D. Scudder, Observations of electron beams in the low-latitude boundary layer, *J. Geophys. Res., 89,* 10723, 1984.

Ogilvie, K. W., et al., SWE, A comprehensive plasma instrument for the wind spacecraft, *Space Sci. Rev., 71,* 55, 1995.

Russell, C. T., R. C. Snare, J. D. Means, D. Pierce, D. Dearborn, M. Larson, G. Barr, and G. Le, The GGS/polar magnetic field investigation, *Space Sci. Rev., 71,* 563, 1995.

Sandholt, P. E., C. J. Farrugia, J. Moen, Ø. Noraberg, B. Lybekk, T. Sten, and T. Hansen, A classification of dayside auroral forms and activities as a function of interplanetary magnetic field orientation, *J. Geophys. Res., 103,* 23325, 1998.

Scearce, C. S., C. V. Moyer, R. P. Lepping, and N. F. Ness, GSFC magnetic field experiments, Explorers 47 and 50, Rep. X-695-76-191, NASA Goddard Space Flight Cent., Greenbelt, Md., Oct. 1976.

Sckopke, N., G. Paschmann, G. Haerendel, B. U. Ö. Sonnerup, S. J. Bame, T. G. Forbes, E. W. Hones Jr., and C. T. Russell, Structure of the low-latitude boundary layer, *J. Geophys. Res., 86,* 2099, 1981.

Scudder, J. D., et al., Hydra: A three-dimensional electron and ion instrument for the polar spacecraft of the GGS mission, *Space Sci. Rev., 71,* 459, 1995.

Sonnerup, B. U. Ö., Theory of the low-latitude boundary layer, *J. Geophys. Res., 85,* 2017, 1980.

Tsyganenko, N. A., A magnetospheric magnetic field model with a warped tail current sheet, *Planet. Space Sci., 37,* 5, 1989.

Tsyganenko, N. A., and D. P. Stern, Modeling the global magnetic field of the large-scale Birkeland current systems, *J. Geophys. Res., 101,* 27,187, 1996.

Winningham, J. D., F. Yasuhara, S.-I. Akasofu, and W. J. Heikkila, The latitudinal morphology of 10-eV to 10-keV electron fluxes during magnetically quiet and disturbed times in the 2100-0300 MLT sector, *J. Geophys. Res., 80,* 3148, 1975.

Yamauchi, M., R. Lundin, L. Eliasson, S. Ohtani, and J. H. Clemmons, Relationships between large-, meso, and small-scale currents and their current carriers, in *Polar Cap Boundary Phenomena,* edited by J. Moen, A. Egeland, and M. Lockwood, pp. 173-188, Kluwer Acad., Norwell, Mass., 1998.

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Figure 1. IMP 8 (dotted line) and Wind (solid line) data for November 30, 1997, showing from top to bottom the IMF components B_X, B_Y, B_Z, plotted against the time of the IMP 8 observations. The Wind data have been lagged by the drift time between Wind and IMP 8 (approximately 56 min).

Figure 2. Cartoon showing the positions of the types 3 and 4 auroral structures observed on November 30, 1997, in the ionosphere. The directions of geographic north (N), south (S), east (E), west (W), and magnetic north (MN) are indicated around the outside of the figure. The line of constant geomagnetic latitude through Ny-Ålesund is shown for reference. Type 3 diffuse aurora is represented by the shaded area. The time-varying type 4 aurora is shown schematically by the discrete oval forms. Arrows indicate the directions of perceived motions from examination of a series of images.

Figure 3. Cartoon showing where the aurora in the ionosphere map to in the magnetosphere. The top sketch shows the locations of the type 3 (shaded region) and type 4 (hash lines) auroral structures as observed in the ionosphere. The layout is the same as Figure 2. The bottom sketch shows where these aurora mapped to in the equatorial plane of the magnetosphere. The location of the Earth is shown as a circle in the center of sketch.

Plate 1. Polar/Hydra data for November 30, 1997, from 0500 to 0730 UT, showing from top to bottom the energy time spectrograms for (a) ions, (b) ion anisotropy, (c) ion skew, (d) electron anisotropy, (e) electrons, (f) B56 component of the magnetic field, and (g) the integrated electric potential and (h) electric field component along the spacecraft velocity vector in a corotating frame of reference. The B56 component of the magnetic field is along the spin axis of the spacecraft and is positive westward.

Plate 2. Time series of red 630.0-nm and green 557.7-nm ASC images for November 30, 1997. Overlapped on the plots are the foot points of Polar. A circle shows the location of Polar at the time the image was recorded. The MLT of Ny-Ålesund is MLT = UT + 3 hours.